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DEVELOPMENT OF FIBER OPTIC SYSTEMS FOR RECORDING AND  
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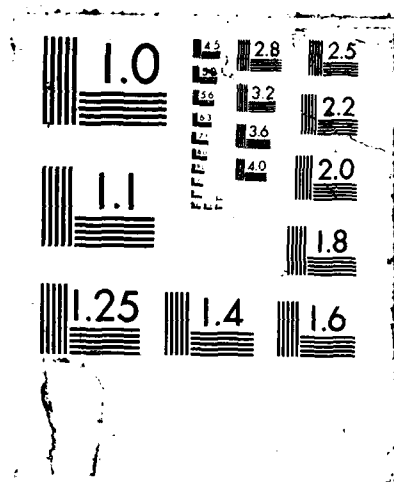
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DEVELOPMENT OF FIBER OPTIC SYSTEMS FOR RECORDING  
AND TRANSMITTING HOLOGRAPHIC INFORMATION

FINAL REPORT

by

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December 1, 1987

U. S. ARMY RESEARCH OFFICE

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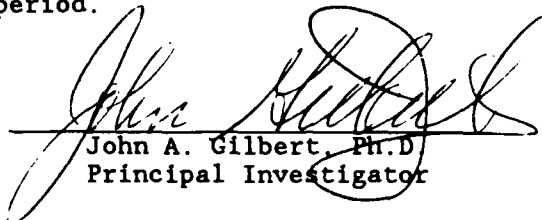
The aim of the research conducted under this contract was to design and test self-contained, automated, fiber-based, optical systems to measure displacement in production-related or dynamic-testing applications where currently existing holographic/fiber optic techniques would be difficult or impossible to apply. This work was suggested while the principal investigator was at the University of Wisconsin in Milwaukee, and was initially funded by ARO under Contract No. DAAG 29-84-K-0183. The original three-year contract (awarded for the period October 1, 1984 through September 31, 1987) called for 6 phases of research consisting of 22 separate tasks. A letter was submitted to ARO on September 17, 1985 formally requesting that the first year award for the contract be extended through December 1, 1985, at no additional cost to the agency. This action was taken to allow the work and objectives proposed for that period to be completed while the principal investigator transferred his research efforts from the University of Wisconsin-Milwaukee (UWM) to the University of Alabama in Huntsville (UAH). The second year award to UWM was refused and a new proposal was submitted to the ARO for continuation of the project at UAH. This two-year request was subsequently funded for the period December 1, 1985 through November 30, 1987 under ARO Contract No. DAAL 03-86-K-0014. This final report covers research performed under DAAL 03-86-K-0014 during the period December 1, 1985 through November 30, 1987.

We have addressed all, and met mostly all, of the research objectives scheduled under DAAL 03-86-K-0014. Most of that work has been documented. We have recieved reprint requests from investigators throughout the United States, and have replied to inquiries from organizations in eighteen different countries. University/industry/ government interaction has been significant (with Marquette, Iowa State, and Texas A&M Universities; and with AT&T Bell Laboratories, MSFC/NASA, etc.), and we have successfully piloted additional research directions under the contract (as described later in the final report). Many technical societies have invited us to present portions of our work including the American Society of Civil Engineers, the American Society for Metals, the American Society of Mechanical Engineers, the American Society for Nondestructive Testing, the British Society for Strain Measurement, the Optical Society of America, the Society of Photo-optical Instrumentation Engineers, and the Society for Experimental Mechanics. Several students have benefited from the funds made available through ARO under Contract No. DAAL 03-86-K-0014. All three of the undergraduate students working on the contract have been published and one of them won a national award for writing a technical paper on his work. The four graduate students supported under contract are currently working on their doctoral degrees in applied optics at the University of Alabama in Huntsville; one of them was selected as the recipient of the 1987 ASNT Fellowship award for developmental research. Portions of our work have been presented to the Board of Trustees of the Alabama System, to Lieutenant Governor Folsom, to Congressman Beville, and to Senator Heflin's chief administrative assistant. Our work has helped to attract industry to the State of Alabama and has played a major role in promoting Huntsville as one of the high technology centers in the Southeast. We have worked with high school students in the areas of holo-interferometry and speckle metrology; one of them took first place in physics at the state science fair and did well in international competition. We have trained hundreds of high school science teachers from all over the United States in holography through a joint program with the Alabama Space and Rocket Center. Some of our visitors have contacted Governor Hunt complimenting us on our research efforts; segments on our laboratories and developmental research have been aired on ABC, CBS, and NBC television.

In short, the work conducted under this research contract has allowed the principal investigator to develop a very strong research program in

engineering mechanics and applied optics at the University of Alabama in Huntsville. To date, thirty publications and presentations have resulted from this two-year contract. We have published in Experimental Mechanics, Optics and Lasers in Engineering, Optical Engineering, Experimental Techniques, Applied Optics, and the Journal of Nondestructive Evaluation. Seven students have been funded; six of which were U.S. citizens.

Special thanks are extended to Dr. E. Saibel and Dr. R. Singleton of the Army Research Office in Research Triangle Park for their invaluable guidance and cooperation throughout the contractual period.



John A. Gilbert, Ph.D.  
Principal Investigator

THE VIEW, OPINIONS, AND/OR FINDINGS CONTAINED IN THIS REPORT ARE THOSE OF THE AUTHOR AND SHOULD NOT BE CONSTRUED AS AN OFFICIAL DEPARTMENT OF THE ARMY POSITION, POLICY, OR DECISION, UNLESS SO DESIGNATED BY OTHER DOCUMENTATION.

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## STATEMENT OF THE PROBLEM STUDIED

The fundamental concept of holographic recording was demonstrated nearly forty years ago when Dennis Gabor suggested the process as a possible means of improving the resolving power of the electron microscope. It was not until the early 1960's, when Leith and Upatnieks produced the first high quality holographic image using a strong coherent source, that widespread attention was given to holography. The exactness of the holographic image made it invaluable for detecting faults by optical interference, and holographic interferometry has since become an important diagnostic tool in non-destructive testing.

Most of the developmental research in holographic interferometry was conducted under laboratory conditions. More recently, however, the technique has attracted the attention of the industrial and military sectors and substantial efforts have been directed toward making holographic measurements under "field" conditions. The ideal holographic measurement system should be robust enough to be transported by road, lift, crane, etc. to its point of operation without becoming misaligned, flexible enough to enter regions with limited access, and capable of being rapidly modified to meet unexpected requirements. Operation should be possible under adverse environmental conditions, response time should be immediate, and most importantly, results should be readily interpretable by a user relatively unfamiliar with the technology underlying the system.

A decade ago, these requirements could not have been met. Lasers were fragile and sensitive to changes in their operating environments; holographic systems had to be located on an isolated optical bench and were constructed using a multitude of mirrors, beamsplitters, lenses, and spatial filters; measurements were influenced by fluctuations in optical path caused by changes in the surrounding environment; real-time recording was messy and time consuming, requiring a wet cell complete with repositioning micrometers; and, quantitative results were usually extracted by photographing holograms from selected observation positions, scanning the photographs for fringe locations, and manually feeding this information to a mainframe computer programmed for single or multiple hologram analysis. Results were usually presented in tabular form and computer graphics were rarely incorporated into postprocessing.

In short, holographic interferometry was limited in reaching its full potential largely because of a lack of proper tools and equipment necessary to record and develop holograms, and the inability to quickly access and properly interpret the complicated interference patterns that arise in most practical applications. Other factors which have led to slow acceptance of holographic non-destructive testing include the relatively high cost per hologram, dissatisfaction with reliability and field servicing of lasers, laser safety regulations, the normally slow acceptance rate of new technology, the time consuming process of designing new test procedures for a specific application, and in some cases, the need for a highly skilled operator.

The bulk of the work performed under Contract No. DAAL 03-86-K-0014 describes how fiber optics and recent advances in equipment and image processing can be used to overcome many of the preceding technical difficulties associated with holographic measurement.

In addition to the holographic work, optical fibers and fiber optic systems have been developed and applied in interferometry and high frequency moire, for speckle metrology and hybrid analysis, and to generate acoustic waves in solids for nondestructive evaluation. Several new ideas have been introduced into the literature as outgrowths of holographic/fiber optic testing including



real-time moire interferometry, ultra-low frequency holography, shadow speckle metrology, radial profilometry, line-broadening, and thermal-acousto photonic nondestructive evaluation (TAP). All of these techniques use optical fibers to some degree, and many new fibers and prototypes were evaluated in their advancement.

A summary of the most important results of our work follows. Additional details can be found in the publications and presentations listed throughout the summary.

## SUMMARY OF THE MOST IMPORTANT RESULTS

Fiber optics provide convenience and simplicity when used in holographic applications. Individual single mode fibers may be used to provide object beam illumination for the test subject and/or reference beam illumination for the hologram itself. Fiber optic components may also be used to transmit the reflected wavefront back from the test subject to the hologram. Adding these links facilitates access to test surfaces that may otherwise be optically inaccessible or physically remote from the laser bench or test station where the hologram is recorded.

The overall aim of the work conducted under DAAL 03-86-K-0014 was to design and test self-contained, automated, fiber-based optical systems to measure displacement in production-related or dynamic testing applications. To this end, a series of experiments was conducted to illustrate holographic recording and measurement techniques using single mode fiber optics [1]. Various considerations for the ultimate development of a practical fiber optic device for making in-situ or "production environment" deformation field measurement by continuous wave holographic interferometry were reported [2,3]. Some of these advances were reviewed in a half-day tutorial on holographic nondestructive testing [4]; others were presented as part of a special session devoted to practical applications of fiber optics [5].

Significant progress was made in developing algorithms for effective access and analysis of holographic deformation fringe patterns with automated data processing equipment when a computer based vidicon camera system was used to digitize, store and accurately analyze high-speed photographs taken of real-time holo-interferometric fringe fields [6]. The results of applying this approach at various levels of complexity were reported [7]. This work ultimately resulted in a systematic method for measuring surface deformations which included the use of real-time holographic interferometry, the incorporation of a carrier fringe pattern to achieve fringe linearization, and the application of image digitization and automated computer analysis for rapid quantitative interpretation [8,9].

The use of photoelectronic media (thermoplastics) to holographically record and store information in many of these investigations led to a new displacement measurement technique called real-time moire interferometry [10]. This approach was applied to study deformations in a notched beam subjected to three point loading [11] and the potential of combining such measurements with finite element techniques was demonstrated [12]. Further improvements were made by transferring high frequency gratings to the specimen from appropriately prepared silicon wafers [13] and then analyzing the resulting fringes with a windowing approach developed for holo-interferometry [14].

Progress was reported on generating holograms using short duration pulses (from a pulse laser) transmitted and recorded through a network of fiber bundles [15]. This work led to the development of the TAP technique in which pulse ruby laser light is transmitted through optical fibers to excite acoustic waves in a metal specimen [16-19], such that the waves could be used to detect flaws in much the same way acoustic waves are used to detect flaws in more standard ultrasonic testing. Recent tests show that these waves can be detected using an optical fiber interferometer [20].

A number of new research avenues were uncovered when numerical correlation routines were developed to register high-speed photographs taken of holographic interferograms in real-time [21]. For example, a hybrid approach for stress analysis based on digital correlation methods was demonstrated [22]. The basic idea in the hybrid approach is to combine finite element analysis and experimental measurements to better characterize the behavior of

an existing prototype. In another technique, called "shadow speckle metrology," artificial speckles were projected onto surfaces to measure deflections and to define their contours [23]. Optical fibers were subsequently incorporated into the recording system to allow deformations to be measured in hazardous locations or in remote areas of structural components [24], and tests were conducted on relatively large structural members (18" diameter pipes, 20' long beams, etc.) under field conditions [25,26].

Other outgrowths of ARO work include a technique called "line broadening" for tracking the movements of vibrating objects [27,28], and an approach called "radial profilometry" designed to automatically contour or measure deflections on the inner surfaces of cavities [29]. Advancements in some of these new optical systems for nondestructive testing were recently presented [30].

#### PUBLICATIONS AND PRESENTATIONS UNDER CONTRACT

1. Gilbert, J.A., "Displacement analysis using holographic interferometry," Proc. of the 1986 Spring Conference on Experimental Mechanics, Society for Experimental Mechanics, New Orleans, Louisiana, June 8-13, 1986, pp. 185-191.
2. Gilbert, J.A., Dudderar, T.D., Nose, A., "Remote displacement analysis through different media using fiber optics, Optical Engineering, 24(4): 628-631 (1985).
3. Dudderar, T.D., Gilbert, J.A., Matthys, D.R., "Potential applications of fiber optics and image processing in industrial holo-interferometry," Proc. of the SPIE O-E/LASE'87 Optoelectronics and Laser Applications in Science and Engineering and Symposium on Electronic Imaging Systems and Devices, Volume 746, Los Angeles, California, January 11-16, 1987, pp. 20-25.
4. Gilbert, J.A., "Holographic non-destructive testing," Tutorial T11, SPIE 1986 Cambridge Symposium on Optics and Optoelectronics Advances in Intelligent Robotics Systems, Cambridge, Massachusetts, October 26, 1986, 90 pages.
5. Gilbert, J.A., Dudderar, T.D., "Applications of fiber optics in experimental mechanics," Proc. of the 1987 Spring Conference on Experimental Mechanics, Society for Experimental Mechanics, Houston, Texas, June 15-19, 1987, pp. 176-183.
6. Johnson, H.S., Gilbert, J.A., "Digital analysis of holo-interferometric patterns," Presented at the Sigma Xi Research Day, University of Alabama in Huntsville, Huntsville, Alabama, March 15, 1986.
7. Matthys, D.R., Gilbert, J.A., Dudderar, T.D., "Computer analysis of holo-interferograms," Proc. of the 1986 Spring Conference on Experimental Mechanics, Society for Experimental Mechanics, New Orleans, Louisiana, June 8-13, 1986, pp. 833-838.
8. Matthys, D.R., Dudderar, T.D., Gilbert, J.A., "Automated analysis of holo-interferograms for determination of surface displacement," accepted for publication in Experimental Mechanics, 1987.
9. Matthys, D.R., Gilbert, J.A., Dudderar, T.D., Koenig, K.W., "A windowing technique for the automated analysis of holo-interferograms," accepted for publication in Optics and Lasers in Engineering, 1987.
10. Johnson, H.S., Gilbert, J.A., Matthys, D.R., Dudderar, T.D., "Real-time moire interferometry," Proc. of the 1986 Spring Conference on Experimental Mechanics, Society for Experimental Mechanics, New Orleans, Louisiana, June 8-13, 1986, pp. 964-970.
11. Johnson, H.S., Gilbert, J.A., Matthys, D.R., Dudderar, T.D., "Real-time moire interferometry," (a revised version of reference 10) accepted for publication in Experimental Mechanics, 1987.
12. Gilbert, J.A., Dudderar, T.D., Matthys, D.R., Johnson, H.S., Franzel, R.A., "Two-dimensional stress analysis combining high frequency moire measurements with finite element modeling," Experimental Techniques, 11(3): 24-28 (1987).
13. Johnson, H.S., Gilbert, J.A., "Transferring high frequency Ronchi

patterns from appropriately prepared silicon wafers," Presented at the 1987 Southeastern Symposium on Photomechanics, Gainesville, Florida, March 6-7, 1987.

14. Johnson, H.S., Bennewitz, J.H., Dudderar, T.D., Matthys, D.R., Gilbert, J.A., "New methods for recording and processing high frequency moire patterns," Proc. of the 1987 Spring Conference on Experimental Mechanics, Society for Experimental Mechanics, Houston, Texas, June 15-19, 1987, pp. 62-70.
15. Peters, B.R., Gilbert, J.A., "Transmission of pulsed ruby laser light through fiber optics," Presented at the Sigma Xi Research Day, University of Alabama in Huntsville, Huntsville, Alabama, March 15, 1986.
16. Burger, C.P., Dudderar, T.D., Gilbert, J.A., Peters, B.R., Smith, J.A., Raj, B., "Thermal acousto-optic excitation for non-contacting NDE," Proc. of the 1986 Spring Conference on Experimental Mechanics, Society for Experimental Mechanics, New Orleans, Louisiana, June 8-13, 1986, pp. 680-685.
17. Burger, C.P., Dudderar, T.D., Gilbert, J.A., Peters, B.R., Smith, J.A., Raj, B., "Thermal acousto-optic excitation through fiber optics for NDE," Journal of Nondestructive Evaluation, 7(1): 57-64 (1987).
18. Peters, B.R., Gilbert, J.A., "Thermal acousto-optic non-destructive evaluation," Presented at the 1987 Southeastern Symposium on Photomechanics, Gainesville, Florida, March 6-7, 1987.
19. Peters, B.R., Gilbert, J.A., Burger, C.P., Smith, J.A., Dudderar, T.D., "Laser excitation through fiber optics for detection of surface flaws," American Society for Nondestructive Testing, Atlanta, Georgia, October 1987.
20. Dudderar, T.D., Burger, C.P., Gilbert, J.A., Smith, J.A., Peters, B.R., "The detection and evaluation of ultrasonic waves using single mode fiber optic interferometry," submitted for presentation at the VI International Congress on Experimental Mechanics, Portland, Oregon, June 5-10, 1988.
21. Taher, M.A., Gilbert, J.A., "Digital correlation of projected speckle patterns," Presented at the Sigma Xi Research Day, University of Alabama in Huntsville, Huntsville, Alabama, March 15, 1986.
22. Matthys, D.R., Dudderar, T.D., Gilbert, J.A., Taher, M.A., Johnson, H.S., "Speckle metrology combined with finite element modelling for stress analysis," Optical Engineering, 25(6): 749-753 (1986).
23. Gilbert, J.A., Matthys, D.R., Taher, M.A., Petersen, M.E., "Shadow speckle metrology," Applied Optics, 25(2): 199-203 (1986).
24. Gilbert, J.A., Matthys, D.R., Taher, M.A., Petersen, M.E., "Remote shadow speckle metrology," Proc. of the 1986 Spring Conference on Experimental Mechanics, Society for Experimental Mechanics, New Orleans, Louisiana, June 8-13, 1986, pp. 814-819.
25. Petersen, M.E., "Measurement of surface profiles using a speckle projection technique," 1st. prize winner in the technical paper contest at the 1987 ASCE Southeast Regional Conference of Student Chapters, Orlando, Florida, March 19-22, 1987.
26. Gilbert, J.A., Matthys, D.R., Taher, M.A., Petersen, M.E., "Profiling

structural members using shadow speckle metrology," accepted for publication in Optics and Lasers in Engineering, 1987.

27. Lehner, D.L., Dudderar, T.D., Matthys, D.R., Gilbert, J.A., "Vibration analysis using shadow speckle metrology and line broadening techniques," Proc. of the 1987 Spring Conference on Experimental Mechanics, Society for Experimental Mechanics, Houston, Texas, June 15-19, 1987, pp. 55-61.
28. Gilbert, J.A., Matthys, D.R., Dudderar, T.D., Lehner, D.L., "Vibration analysis using digital correlation," submitted for presentation at the VI International Congress on Experimental Mechanics, Portland, Oregon, June 5-10, 1988.
29. Gilbert, J.A., Greguss, P., Lehner, D.L., Lindner, J.L., "Radial profilometry," Proc. of the Joint BSSM/SEM International Conference on Advanced Measurement Techniques, London, England, August 24-27, 1987.
30. Gilbert, J.A., Johnson, H.S., Peters, B.R., Ruggiero, R.M., "Optical systems for nondestructive evaluation," Proc. of the Nondestructive Evaluation for Aerospace Requirements Conference, Huntsville, Alabama, August 26-27, 1987.

### PARTICIPATING SCIENTIFIC PERSONNEL

The students listed below were partially or fully funded under Contract No. DAAL 03-86-K-0014. All research was conducted under the direct supervision of the principal investigator.

Name: Johnson, H.S.

Remarks: Ms. Johnson worked with the principal investigator in the capacity of graduate research assistant and is currently working on her Ph.D. at the University of Alabama in Huntsville. See reference nos. 6, 10-14, 22, and 30.

Name: Lehner, D.L.

Remarks: Mr. Lehner worked with the principal investigator in the capacity of graduate research assistant and is currently working on his Ph.D. at the University of Alabama in Huntsville. See reference nos. 27-29.

Name: Peters, B.R.

Remarks: Mr. Peters worked with the principal investigator in the capacity of graduate research assistant and is currently working on his Ph.D. at the University of Alabama in Huntsville. He was awarded the 1987 ASNT Fellowship for developmental research on the TAP system. See reference nos. 15-20, and 30.

Name: Taher, M.A.

Remarks: Mr. Taher worked with the principal investigator in the capacity of graduate research assistant and is currently working on his Ph.D. at the University of Alabama in Huntsville. See reference nos. 21-24, and 26.

Name: Lindner, J.L.

Remarks: Mr. Lindner worked with the principal investigator as an undergraduate research assistant. He is currently a junior in mechanical engineering. See reference no. 29.

Name: Petersen, M.E.

Remarks: Mr. Petersen worked with the principal investigator as an undergraduate research assistant. He has been awarded scholarships for his research efforts and won first prize in the technical paper contest sponsored by ASCE. Mr. Petersen is currently a junior in mechanical engineering. See reference nos. 23-26.

Name: Ruggiero, R.M.

Remarks: Ms. Ruggiero worked with the principal investigator as an undergraduate research assistant. She will graduate with her B.S. in electrical engineering this month. See reference no. 30.

Note: J.H. Bennewitz [reference no. 14], R.A. Franzel [reference no. 12], and A. Nose [reference no. 2], worked with the principal investigator as graduate research assistants. These students contributed to the project but were funded from other sources. They have all completed their advanced degrees and are currently employed at AT&T Bell Laboratories, General Electric Medical Systems Division, and Yamaha, respectively.

Note: T.D. Dudderar [reference nos. 2, 3, 5, 7-12, 14, 16, 17, 19, 20, 22, 27, and 28] is a Member of the Technical Staff at AT&T Bell Laboratories in Murray Hill, N.J.

Note: C.P. Burger [reference nos. 16, 17, 19, and 20] is a Professor of Mechanical Engineering at Texas A&M University in College Station, Texas; J.A. Smith [reference nos. 16, 17, 19, and 20] and B. Raj [reference nos. 16 and 17] are graduate students working with Professor Burger.

Note: P. Greguss [reference no. 29] is the Director of the Applied Biophysics Laboratory at the Technical University of Budapest in Budapest, Hungary.

Note: D.R. Matthys [reference nos. 3, 7-12, 14, 22-24, and 26-28] is an Associate Professor of Physics at Marquette University in Milwaukee, Wisconsin; K.W. Koenig [reference no. 9] is a graduate student working with Professor Matthys.



